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Fundamental Investigation Of Whole-Life Power Plant Performance For Enhanced Geothermal Systems

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Fundamental Investigation of Whole-Life Power Plant Performance for Enhanced Geothermal Systems

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ABSTRACT

This paper presents a fundamental investigation of the use of conventional Rankine Cycle, Trilateral Flash Cycle, and wet vapour Rankine Cycle system for the generation of power from Enhanced Geothermal Systems. The paper considers ideal Carnot, Trilateral and Quadlateral cycles, and compares the ideal cases of maximum rate of power production with maximum total electricity delivery. These results illustrate the relative advantages of different power plant systems, and provide insight into the operational requirements of power generation equipment for enhanced geothermal systems. A more detailed analysis is then performed for a recuperated Organic Rankine Cycle. This analysis allows a direct comparison between the ideal and practical cycles, showing maximum cycle efficiencies of around half the ideal Quadlateral Cycle case, and demonstrates some of the challenges associated with designing a system to operate over a wide range of heat source conditions.

1. INTRODUCTION

Enhanced geothermal systems (EGS) have received considerable attention in recent years due to developments in the field of hydraulic fracturing (or 'fracking') for recovering fossil fuels. At many locations, this technology can be used to create a hydraulic circuit with a large contact area between so called 'hot dry rock' and the pressurised hydraulic fluid. At the surface, the heat added to the fluid as it passes through the circuit can be transferred to a secondary fluid for use in a thermal power plant, where a proportion of the heat is converted into electrical energy. Unlike most low temperature heat recovery applications, the EGS can be approximated as essentially a finite energy resource. Various configurations can be considered for the power plant, including the conventional Rankine Cycle, Trilateral Flash Cycle, and wet vapour Rankine Cycle. The main differences relate to the type of expander required, the component sizing and the rate of heat extraction from the hydraulic fluid. Maximising heat extraction leads to increased power output but decreases the temperature of the fluid returning to the geothermal circuit, causing the reservoir temperature to decay more quickly.

2. IDEAL CYCLE ANALYSIS

Carnot, Trilateral and Quadlateral cycles can be considered as ideal cases of thermodynamic plant for the generation of power from an EGS resource. Analysis of these cycles needs to consider:

i. the total amount of work recoverable from a EGS reservoir, assuming it to be a finite heat source
ii. the power output from each system

Fundamental studies of ideal cycle for geothermal applications have previously been investigated (DiPippo, 2007). The application of these ideal cycles to the case of a resource with finite energy, and therefore with variation in the inlet temperature of the geofluid heat source over time, is considered in the following sections.

2.1 Ideal Carnot Cycle

The ideal Carnot Cycle is well known as the thermodynamic cycle achieving maximum efficiency when accepting heat from and rejecting heat to an infinite heat source and sink respectively. However, in cases where the source and sink are finite and their temperatures changes during the heat transfer process, the constant temperature of heat addition to the cycle cannot exceed the exit temperature of the heat source fluid. A suitable temperature of heat addition therefore becomes a compromise between extracting more heat from the source fluid, and maximizing the cycle efficiency, and the optimum value of the temperature of heat addition is found to be $T_1 = (T_0 T_2)^{0.5}$ (Smith, 1992) as shown in Figure 1. While the Carnot Cycle is an idealized thermodynamic cycle, it provides an interesting case study as it can be considered to approximate a Rankine cycle with large evaporative heat transfer.

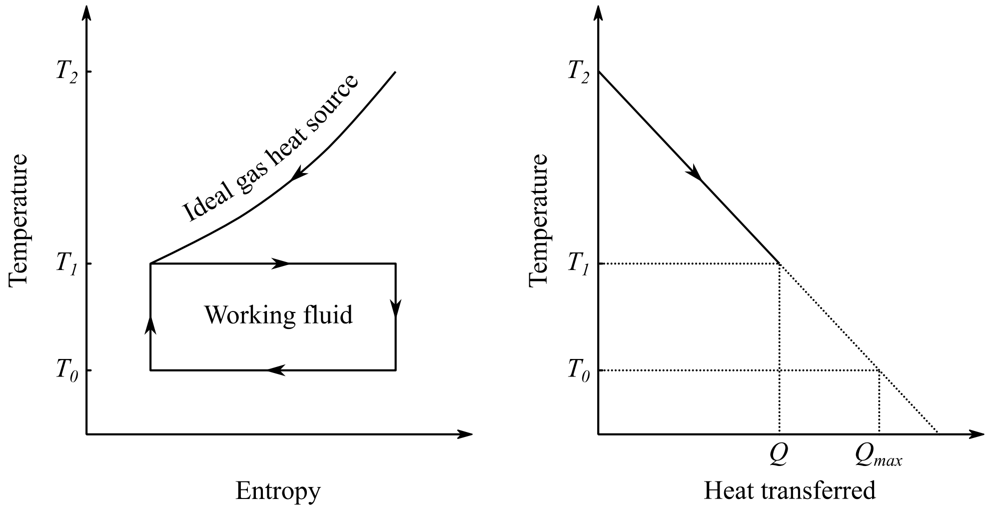

Figure 1 – Illustrations of a) an ideal Carnot Cycle operating with a constant pressure ideal gas heat source and b) the associated heat transfer limitations that restrict the total heat recovery

Using standard expressions for the efficiency of the Carnot Cycle, the following equations can be derived for the 'optimum' case when the power output is maximized. The total amount of work produced by the cycle As the source temperature decreases from its initial value of T_1 to the final sink temperature of T_0 (which occurs when all available energy has been removed from the resource) can therefore be expressed as follows.

$$\eta_{cyc} = \frac{(T.T_o)^{0.5} - T_o}{(T.T_o)^{0.5}}$$

$$\frac{dW}{dT} = \dot{m}.c_p.\left(\frac{(T.T_o)^{0.5} - T_o}{(T.T_o)^{0.5}}\right)$$

$$\therefore\ W_{total} = \dot{m}.c_p.\int_{T_o}^{T_1} \left(\frac{(T.T_o)^{0.5} - T_o}{(T.T_o)^{0.5}}\right).dT$$

2.2 Ideal Trilateral Cycle:

The ideal Trilateral Cycle corresponds to the maximum recovery of power from heat sources on which there are no restrictions to cooling to the available sink temperature, as shown in Figure 2. It can be considered as a series of infinitesimal Carnot Cycles operating between the decreasing source temperature and the sink temperature. This cycle corresponds to maximum heat recovery and therefore approximately represents the TFC system, as proposed by Smith (1993, 1996), or a supercritical Rankine cycle with no recuperative heat exchange.

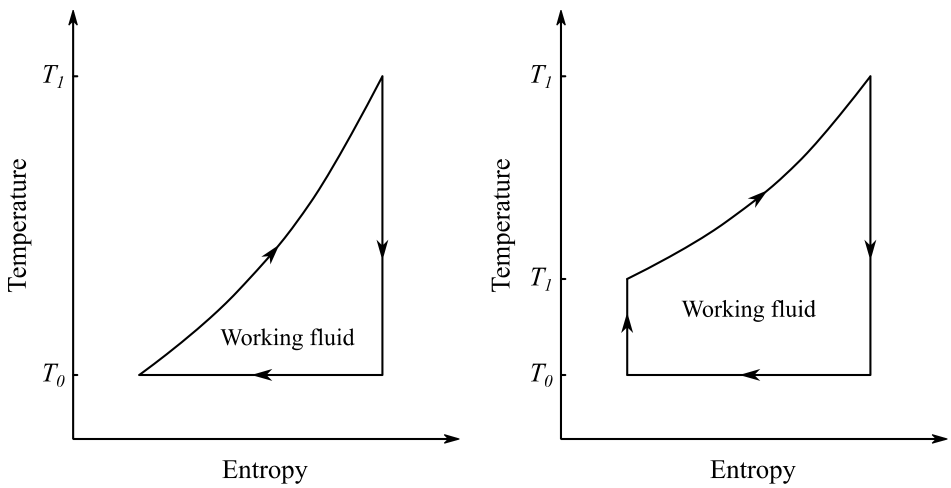

Figure 2 – Illustrations of ideal Trilateral Cycle and Quadlateral Cycle with constant pressure single phase heat source

The efficiency and total workfor the Trilateral Cycle can be derived by considering the integral of infinitesimal Carnot Cycles (Smith, 1992) resulting in the following equations.

$$\eta_{cyc} = 1 - \frac{T_o.ln(T/T_o)}{T - T_o}$$

$$\frac{dW}{dT} = \dot{m}.c_p.\left(1 - \frac{T_o.ln(T/T_o)}{T - T_o}\right)$$

$$\therefore W_{total} = \dot{m}.c_p.\int_{T_o}^{T_1}\left(1 - \frac{T_o.ln(T/T_o)}{T - T_o}\right).dT$$

2.3 Ideal Quadlateral Cycle:

The ideal Quadlateral Cycle corresponds to the case where the source fluid may not be cooled excessively, such as combustion products, as shown in Figure 2. This is an interesting case to investigate for finite energy sources, as it may be thermodynamically advantageous to limit the temperature drop of the geofluid during heat addition to the cycle. The Quadlateral Cycle can be considered to correspond approximately to a superheated or supercritical Rankine cycle with a large recuperator or to the ‘Smith cycle’ where one expands liquid partially, in a two-phase expander and then separates the phases, with the vapour continuing to expand in a turbine and the liquid readmitted to that leaving the feed pump so that the liquid mixture is heated prior to entering the feed heater.

The Quadlateral Cycle can be investigated by considering two Ideal Trilateral cycles, one operating between T_0 and T_1 and subtracting from it another operating between T_0 and T_2, as shown in Figure 3.

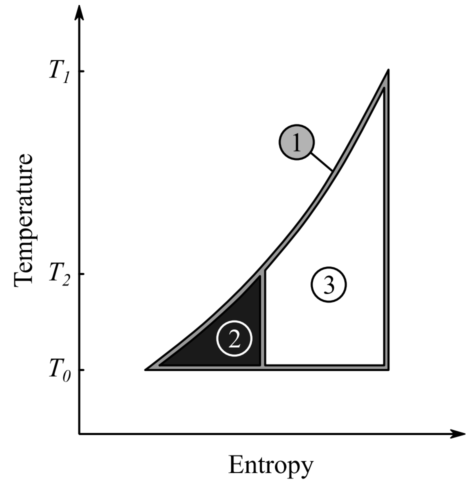

Figure 3 – Illustration of ideal Quadlateral Cycle (3) as the difference between a high temperature Trilateral Cycle (1) operating between T_0 and T_1, and a low temperature Trilateral Cycle (2) operating between T_0 and T_2

The total work done by the Quadlateral Cycle can be considered as the difference between that of the two Trilateral Cycles. It is also possible to derive an expression for the efficiency of the Quadlateral Cycle as a function of the source, sink and intermediate temperatures, as shown. Here the geofluid exit temperature may be varied by varying x, where $T_2 \ = \ T_0 + \ x(T - T_0)$.

$$W_{total} = \dot{m}.c_p.\int_{T_o}^{T_1}\left(1 - \frac{T_o.ln(T/T_o)}{T - T_o}\right).dT - \ \dot{m}.c_p.\int_{T_o}^{T_2}\left(1 - \frac{T_o.ln(T/T_o)}{T - T_o}\right).dT$$

$$\eta_{cyc} = 1 - \frac{T_o.ln(T/T_2)}{(T - T_2)}$$

2.4 Results of Ideal Cycle Analysis

The study determines the power outputs from these ideal cycle systems. This was done by multiplying the cycle efficiency by the specific heat capacity of the geofluid multiplied by the temperature drop of the geofluid in each system. Not surprisingly the Trilateral gives the highest power output per kg/s and the Carnot, the lowest.
Thus, the Carnot system runs for nearly twice the time that the Trilateral system does if the mass flow rate of the geofluid is fixed, and the total work output is approximately the same. The results for cycle efficiency, specific power and geofluid inlet and return temepratures are shown for all cycle sin Figures 4 and 5. The effect of the heat removed from the geofluid on the evolution of the source temperature has been investigated by defining a finite initial energy content of the resource. Assuming a constant circulating flow rate of the geofluid, the higher the rate of heat extraction in the cycle the quicker the resource is deleted and the faster the temperature of the geofluid at the inlet to the cycle falls. The inlet temperature of the geofluid is shown in Figure 5 as a function of time. Figure 6 shows the results for the specific power output and total cumulative energy production as functions of time normalized by the time take for the ideal Trilateral Cycle to deplete the geofluid inlet temperature from 200 to 100ºC

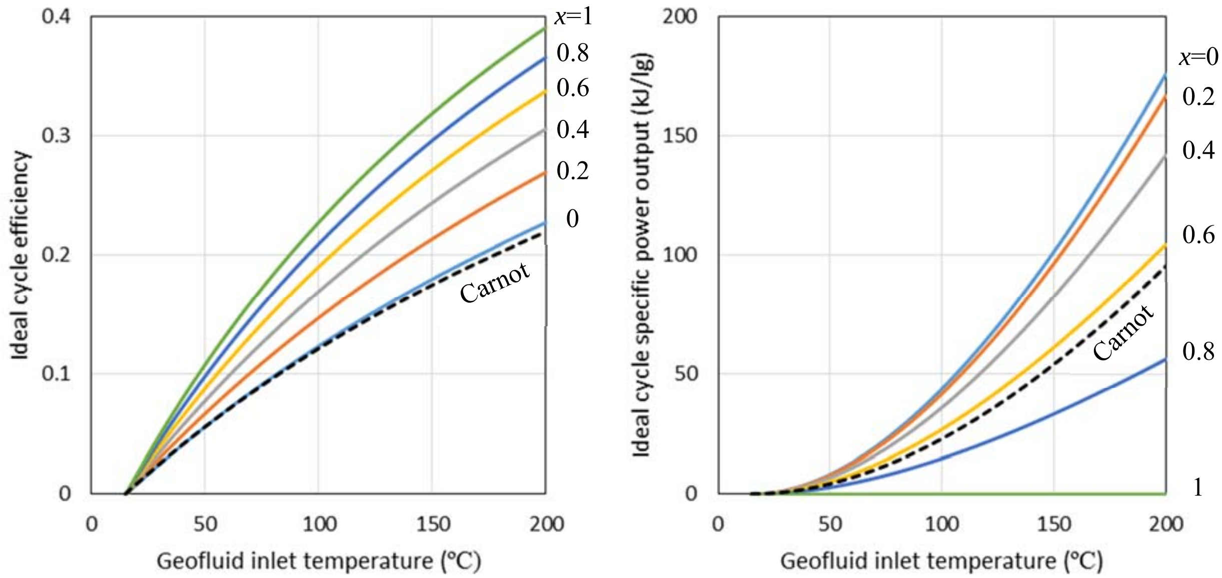

Figure 4: Cycle efficiency and power output per unit geofluid mass flow rate as a function of geofluid inlet temperature for the ideal Carnot, Trilateral and Quadlateral Cycles with $x = 0.2, 0.4, 0.6, 0.8$ and 1

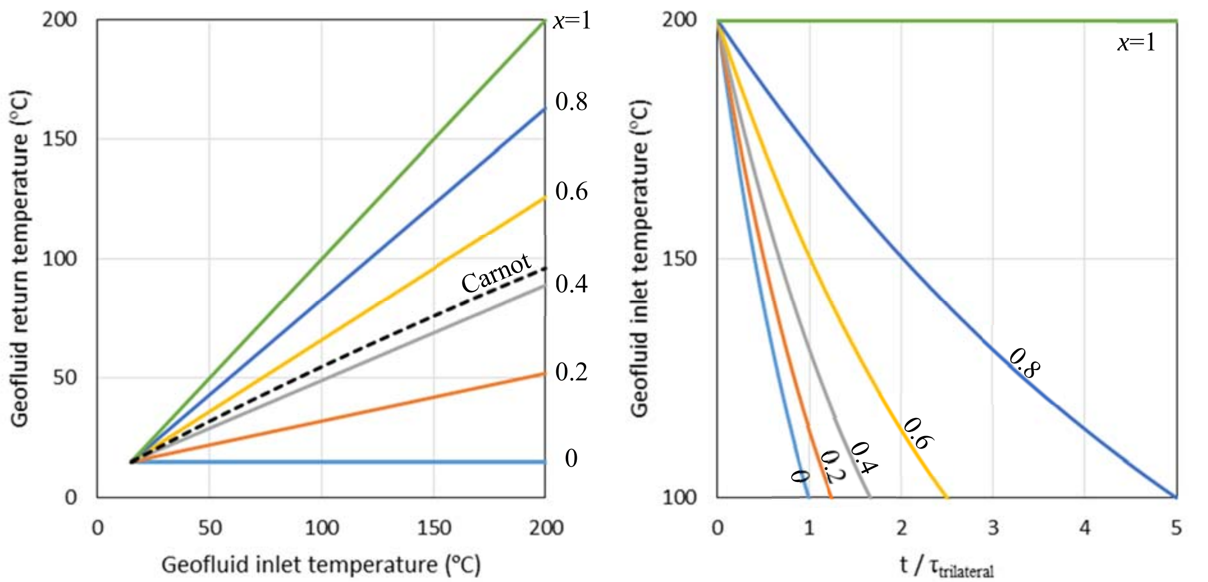

Figure 5: Geofluid return temperature as a function of the inlet temperature, and the inlet temperature a function of time for the ideal Carnot, Trilateral and Quadlateral Cycles (note that $\tau_{trilateral}$ is the time taken for the geofluid temperature to fall from 200 to 100ºC using the Trilateral Cycle)

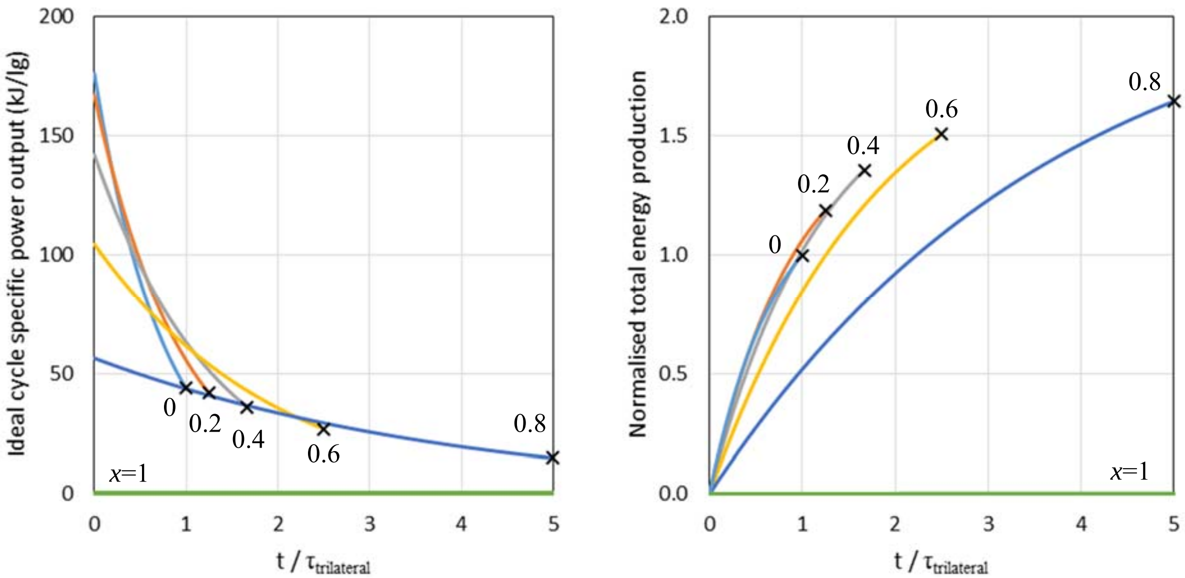

Figure 6: Power output per unit geofluid mass flow rate and the normalized cumulative energy production as functions of time for the ideal Trilateral Cycle and ideal Quadlateral Cycles (note that results are only shown for inlet temperatures down to 100ºC, which is indicated with an X)

The ideal trilateral and the Carnot cycle systems produce almost the same total work output but the power output from the Ideal Trilateral Cycle system is approximately 80% more than from the Carnot cycle system. It follows that the life of the resource would be roughly 80% greater for the Carnot cycle to produce the same total output. Clearly the irreversibility associated with heat transfer in the boiler, in the case of the Carnot Cycle, is almost identical with the irreversibility associated with heating up the cooled fluid returned to the reservoir in the Trilateral Cycle. On this basis, there is little doubt that a saturated vapour ORC system will almost certainly produce more output over the life of the reservoir, than either a supercritical or TFC system, because, the work ratio of the saturated vapour ORC is significantly better than either of the other two, while, due to the larger $LMTD$ for heat addition and the resulting smaller boiler, it will be far cheaper to install.

The Trilateral Cycle maximises the power recovery at every stage of the cooling process but has large irreversibilities in returning the geofluid to the hot rock at minimum temperature, which then has to be reheated. The Quadlateral Cycle returns the geofluid at a higher temperature. Therefore, there is less irreversibility in the whole process of reheating but this is done by withdrawing less heat at each stage. Hence, as the geofluid return temperature is increased, the overall efficiency and, hence total recoverable work increases but the power goes down. In the limit, as the geofluid return temperature approaches the geofluid inlet temperature, the recoverable work approaches a maximum and the efficiency of each stage of the process approaches that of a Carnot Cycle working between the same temperature limits, but the power output, associated with this tends to zero, since the heat recovered, as the system produces work, is negligible at each stage. Therefore, in the Quadlateral Cycle case the selection of a value of an appropriate value of x is essentially a choice between the maximum rate of power recovery for the Trilateral Cycle and maximum recoverable work at a negligible power generation rate, in the limit, when the heat withdrawal rate tends to zero.

A more detailed consideration of the cycle performance is required in order to assess the achievable cycle efficiency and to investigate how the varying temperature of the heat source might influence the power plant selection and design.

3. DETAILED CYCLE ANALYSIS

A starting point for investigating the effect of cycle configuration on efficiency is the conventional ORC with recuperation. As the initial source fluid is relatively high, organic fluids such as pentane and siloxanes such as MM (hexamethyldisiloxane) can be used in conventional ORCs with dry vapour expansion. The saturation envelopes of these fluids are shown in Figure 7, and an illustration of the recuperated cycle is shown in Figure 8. There are a number of issues with using these types of organic fluids in a power generation cycle. The flammability and explosion risks of pure hydrocarbons are high, although the risks are lower with fluorocarbons and siloxanes. Additionally, as with conventional steam Rankine cycles, the pressure required in the condenser is sub atmospheric in order to maximise net power output, which creates problems with sealing the system and also leads to high volumetric flow rates and correspondingly large components. The pressure ratio across the expander can also be large, making the design of efficient single stage turbines difficult or impossible.

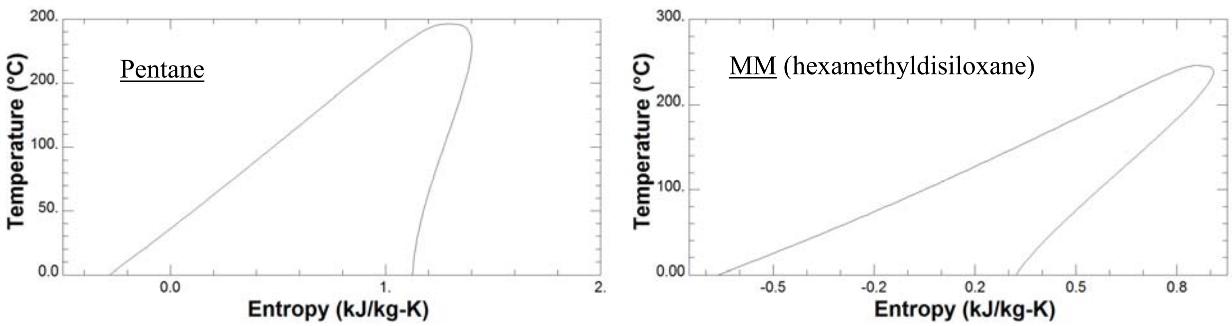

Figure 7: Saturation envelopes of pentane and MM

With dry vapour expansion there is usually a large degree of superheat at the expander exit, which requires an internal heat exchanger, known as a recuperator, to transfer heat from the superheated vapour to the subcooled liquid exiting the pump. This component can be a significant additional expense due to its potentially large size; a result of high volumetric flow rate, low log-mean temperature difference ($LMTD$) and low overall heat transfer coefficient.

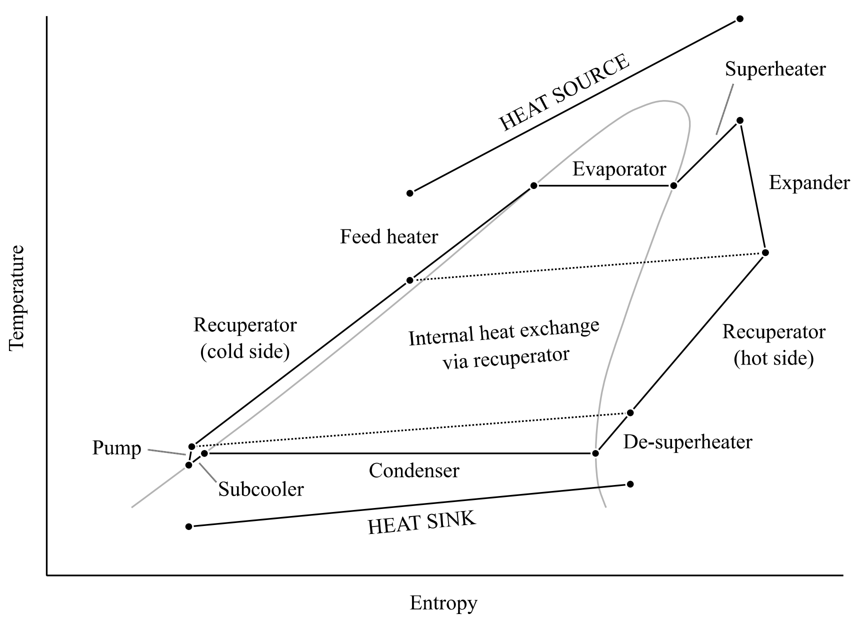

Figure 8: Illustration of ORC with recuperation showing processes in each of the main components and heat exchangers

The pinch point that occurs between the subcooled and superheated fluids in the recuperator heat exchanger has a strong influence on the power output of the cycle. If the pinch point is large then less heat is transferred internally and more heat is rejected in the condenser. If the pinch point is small, less heat is rejected, but the required surface area of the recuperator is larger due to the smaller $LMTD$. Recuperator effectiveness has been defined as shown in Equation 1, where the subscript hot refers to the superheated vapour stream leaving the turbine, and $cold$ refers to the subcooled liquid stream leaving the feed pump:

$$\varepsilon_{recup} = \left(h_{cold,o} - h_{cold,i}\right)/\left(h_{hot,i} - h_{cnd,i}\right) \qquad (1)$$

By specifying the value of ε_{recup} along with the feed pump and expander outlet conditions it is possible to determine the conditions of the hot and $cold$ fluids at the outlet of the recuperator, and the pinch point that occurs in the recuperator can then be calculated. Pressure drops in heat exchangers and piping has been neglected in the following analysis, as it requires detailed consideration of component design and layout that is beyond the scope of the present study. Sub-cooling of 2ºC has been applied in order to prevent cavitation in the feed pump.

By specifying a minimum allowable geofluid return temperature, the recuperated ORC can be optimized to find the boiler pressure, condenser pressure and degree of superheat that result in the maximum net power output per unit geofluid mass flow rate. This has been performed for a range of geofluid return temperatures for an ORC using pentane working fluid and the representative cycle parameters shown in Table 1, and the results are shown in Figures 9-10.

Table 1: Cycle Parameters for recuperated ORC study

Working fluid	Pentane
Heat exchanger pinch points	5ºC
Feed pump efficiency	70%
Condenser fan efficiency	75%
Generator efficiency	95%
Motor efficiency	90%
Recuperator effectiveness	90%

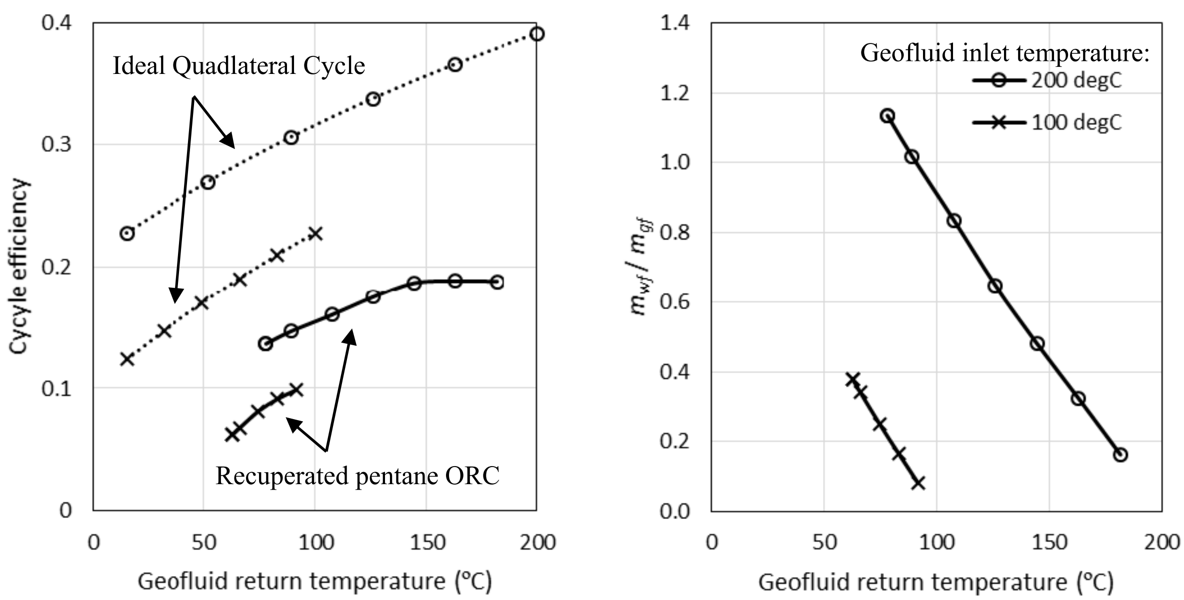

Figure 9: Maximum cycle efficiency and the required working fluid mass flow rate as a function of geofluid return temperature for a recuperated ORC using pentane working fluid and the parameters specified in Table 1 (note comparison of efficiency with the ideal Quadlateral case)

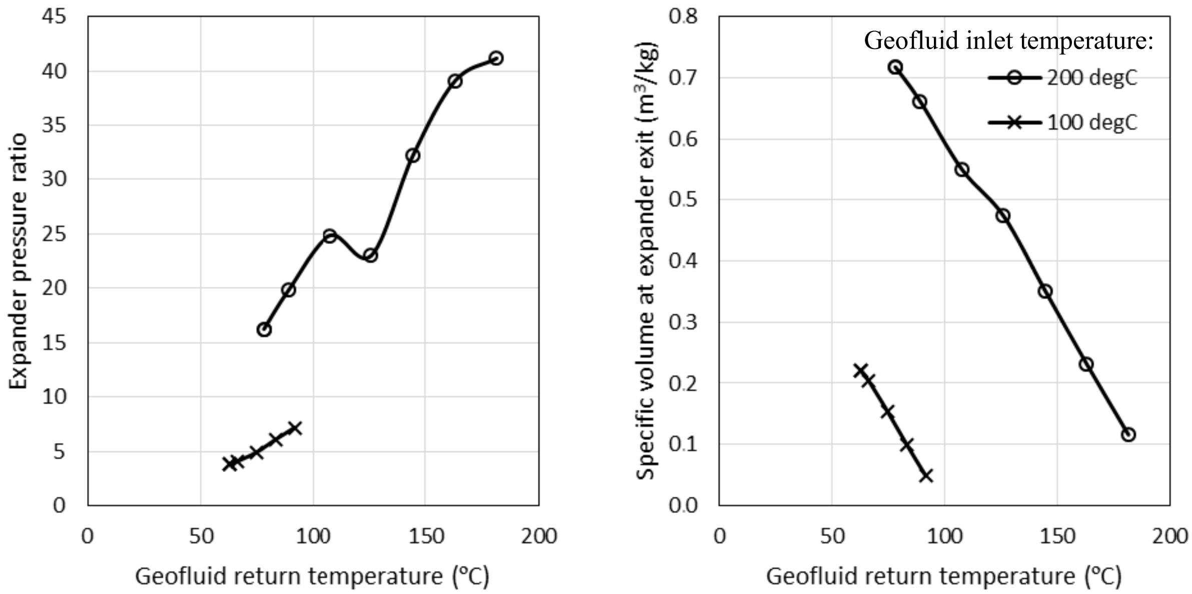

Figure 10: Expander pressure ratio and exit specific volume for a recuperated ORC using pentane working fluid and the parameters specified in Table 1

It is clear from Figure 9 that a recuperated ORC is capable of achieving a cycle efficiency of around half that of the ideal Quadlateral Cycle for a given geofluid return temperature. There are however large changes in the required operating conditions as the temperature of the geofluid declines with time. Changes in the required mass flow rate in the cycle will affect the performance of the pump and expander components, while the expander pressure ratio and volume flow rate will also change significantly. It is difficult to see how a single system could be made to operate efficiently over such a wide range of operating condition. One option would be to periodically modify components and/or operating characteristics such as speed, in order to maintain a reasonable match between the cycle and the source fluid temperature. It may aslo be practical to consider periodically replacing the working fluid itself in order to maintain efficient operation of the expander, although this would require careful design and optimization of the cycle. Other alternatives include the use of additional heat sources to maintain a constant geofluid inlet temperature. This could be achieve either by the phased development of additional enhanced geothermal resources or through the use of additional heat source such as biofuels to supply additional heat to the fluid prior to the cycle. In this case, the EGS can be thought of as a preheater for a more conventional high temperature power generation cycle, which could be particularly attractive for biofuel applications where the combustion gasses cannot be cooled much below 200ºC to prevent the formation of corrosive condensates.

This initial study indicates that good cycle performance can be achieved across the expected range of operating conditions. The component design, cycle optimization and control are however challenging for a practical application of a system, and methods of maintaining a high geofluid inlet temperature across the life of the resource is likely to be key to achieving an efficient and cost effective system. Future work will investigate how the operation of a fully specified ORC system can be optimized for off-design conditions that occur as the EGS reservoir temperature decrease, and will seek to identify the practical limitations for power generation and total energy recovery.

4. CONCLUSIONS

The performance of ideal cycles has been investigated for the case of an EGS resource approximated as a finite energy heat source. A more detailed study of a recuperated ORC with representative operational parameters was then performed to investigate the effect of component losses and finite temperature differences for heat transfer on the overall system performance. The main conclusions of the current study are as follows:

- When considering the ideal cycles, the Trilateral case maximizes the specific power output as a function of the geofluid inlet temperature, but results in low total work done as a function of the reservoir temperature due to the irreversibility's that occur due to the low temperature heat addition to the cycle.
- The optimum Carnot Cycle has very similar cycle efficiency as the Trilateral, but the higher return temperature leads to low power output and slower decay of the reservoir temperature.
- The Quadlateral case allows the heat addition to occur at higher temperatures. For a particular geofluid return temperature this allows higher cycle efficiency to be achieved than the Carnot Cycle and hence a greater total energy recovery over the life of the resource.
- The detailed analysis of a recuperated ORC system for geofluid inlet temperatures of 200 and 100ºC shows that a real cycle efficiency around half that of the ideal Quadlateral Cycle is feasible. However, the component and system requirements vary greatly with the reservoir conditions, and further studies are required to analyse how the time varying EGS resource may be best utilized for efficient and cost effective power generation.

NOMENCLATURE

EGS	Enhanced Geothermal System
ORC	Organic Rankine Cycle
TFC	Trilateral Flash Cycle
LMTD	Log Mean Temperature Difference
h	Enthalpy
η	Efficiency
ε_{recup}	Recuperator effectiveness
W	Work done

Subscript

$hot/cold$	Higher or lower temperature fluid in recuperator

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